

Estimating suspended sediment concentrations in turbid coastal waters of the Santa Barbara Channel with SeaWiFS

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Abstract. A technique is presented for estimating suspended sediment concentrations of turbid coastal waters with remotely sensed multi-spectral data. The method improves upon many standard techniques, since it incorporates analyses of multiple wavelength bands (four for Sea-viewing Wide Field of view Sensor (SeaWiFS)) and a nonlinear calibration, which produce highly accurate results (expected errors are approximately $\pm 10\%$). Further, potential errors produced by erroneous atmospheric calibration in excessively turbid waters and influences of dissolved organic materials, chlorophyll pigments and atmospheric aerosols are limited by a dark pixel subtraction and removal of the violet to blue wavelength bands. Results are presented for the Santa Barbara Channel, California where suspended sediment concentrations ranged from 0-200+ mg 1^{-1} (± 20 mg 1^{-1}) immediately after large river runoff events. The largest plumes were observed 10-30 km off the coast and occurred immediately following large El Niño winter floods.

1. Introduction

Multi-band sensors, such as the Sea-viewing Wide Field of view Sensor (SeaWiFS), provide ideal opportunities to investigate coastal suspended sediment distributions, which are often expensive and difficult to monitor (Geyer *et al.* 2000, Stumpf and Goldschmidt 1992). Suspended sediment concentrations affect remotely sensed signals through the interactions of scattering and absorption by sediment particles and water. Summaries of these relationships are provided by Kirk (1994) and Warrick (2002). In general, the optics of water–sediment mixtures are highly nonlinear, while many factors such as suspended particle size, shape and colour can have large influences on water–sediment optics (Pak *et al.* 1970, Pollack and Cuzzi 1980, Baker and Lavelle 1984, Stumpf and Pennock 1989, Kirk 1994, Sydor and Arnone 1997). Due to these optical complexities it is well known that there are no universal algorithms to remotely estimate sensed sediment concentrations.

Here, a variation of the spectral mixture analysis (SMA) technique of Mertes *et al.* (1993) is reported, modified to estimate suspended sediment concentrations of river

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plumes in the Santa Barbara Channel, California. Adequate field data were collected in the river plumes of the channel to properly calibrate the SeaWiFS imagery.

2. Spectral mixture analysis

Spectral mixture analysis (SMA) is a multiple band analysis that uses endmembers to characterize gradients within remote sensing images (Smith *et al.* 1990). The optical characteristics of these end-members can be defined using reflectance data from a remotely sensed image or from importing other *in situ*- or laboratory based optical information. Using the end-members, the best-fit fraction (F_i) of each end-member (i) is computed for each pixel using a least-squares solution of:

$$R_b = \sum_{i=1}^{n} F_i R_{i,b} + E_b \tag{1}$$

and,

$$\sum_{i=1}^{n} F_i = 1 \tag{2}$$

where R_b is the reflectance in band b of an image pixel, F_i is the fraction of endmember i, $R_{i,b}$ is the reflectance of end-member i in band b, n is the number of endmembers, and E_b is the error for band b of an image pixel. The rms error (ε) for each pixel is:

$$\varepsilon = \left[N^{-1} \sum_{b=1}^{n} E_b^2 \right]^{1/2} \tag{3}$$

3. Image processing

An important goal in this analysis was to simultaneously preserve important water-leaving reflectance ($\rho_{\rm w}$) measurements, especially in the red and near-infrared (NIR) spectrum (Stumpf and Pennock 1989), and accurately correct atmospheric conditions in the SeaWiFS imagery. Unfortunately, these two goals are in opposition (e.g. Gould and Arnone 1997a), since the NIR radiances are utilized to correct for atmospheric aerosols (Gordon and Wang 1994, Ruddick *et al.* 2000, Siegel *et al.* 2000) and coincidentally needed to accurately estimate sediment concentrations (Witte *et al.* 1981). Thus, to remove atmospheric reflectance ($\rho_{\rm atm}$) from the total measured reflectance by the SeaWiFS sensor ($\rho_{\rm t}$) the dark-pixel method was employed.

For imagery acquired in non-cloudy conditions, the ρ_t of the darkest single ocean pixel is assumed to be contributed entirely from the atmosphere (i.e. ρ_{atm}) and was subtracted from the ρ_t of each pixel according to:

$$\rho_{\rm w}(\lambda) = \frac{\rho_{\rm t}(\lambda) - \rho_{\rm atm}(\lambda)}{T_{\rm v}(\lambda)} \tag{4}$$

where $T_{\rm v}$ is the viewing diffuse atmospheric transmittance, which was obtained from the SeaWiFS Data Analysis System (SeaDAS) level 2 products for non-turbid water pixels in each scene, so they were not biased over turbid water pixels. In choosing a dark pixel, preference was given to offshore ocean pixels unaffected by shade, clouds and land, and to SeaWiFS band 5 (555 nm), since this band is both highly sensitive to lower suspended sediment concentrations (Kirk 1994) and is not impacted by light absorption from phytoplankton pigments (Gordon *et al.* 1983).

Unwanted pixels of haze, cloud and land were removed using the relatively

constant reflectance signatures across the visible and NIR bands (Jensen 2000). Thus, these unwanted pixels were disregarded by subjectively removing all pixels with both non-zero $\rho_w(865)$ and low ratios of $\rho_w(555)$ to $\rho_w(865)$. For SeaWiFS imagery of the Santa Barbara Channel, adequate thresholds were found to be:

$$\rho_{\rm w}(865) > 0.0025 \tag{5}$$

and,

$$\frac{\rho_{\rm w}(555)}{\rho_{\rm w}(865)} < 1.5 \tag{6}$$

These values eliminated nearly all haze, cloud and land pixels (including mixed pixels), while preserving turbid and clear water pixels for suspended sediment concentration analysis.

Chromophoric dissolved organic matter (cdom) and chlorophyll pigments, if present, were a concern since they tend to have very strong light absorption properties, especially in violet and blue wavelengths (Carder *et al.* 1989, Kirk 1994, Toole and Siegel 2001). These effects were minimized by removing SeaWiFS bands 412, 443, 490 and 510 nm. Removing these bands also eliminated the wavelengths with the largest atmospheric aerosol impacts (Gordon and Wang 1994, Gould and Arnone 1997b). Thus, the four remaining SeaWiFS bands (555, 670, 765 and 865 nm) have the greatest spectral response to suspended sediment concentrations (Witte *et al.* 1981) and the least impacts from cdom, chlorophyll pigments and atmospheric aerosol variability.

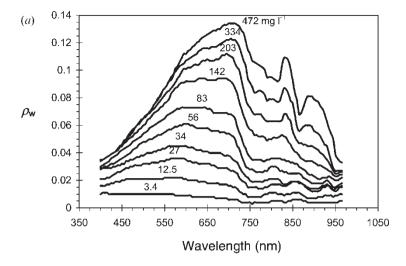
4. Sediment calibration

Suspended sediment concentration was evaluated for each pixel by conducting an SMA, which was calibrated with laboratory reflectance measurements of Witte *et al.* (1981; figure 1(*a*)). The Witte *et al.* (1981) data compared well with *in situ* $\rho_{\rm w}$ measurements within the Santa Clara River plume (figure 1(*b*)). The spectra for sediment concentrations of ca $50\,{\rm mg}\,{\rm l}^{-1}$ are within $\pm 10\%$ at all wavelengths > 500 nm. The spectra for concentrations of ca $20\,{\rm mg}\,{\rm l}^{-1}$ are within $\pm 15\%$ between 500 nm and 750 nm. However, these spectra sets do deviate, which may be due to the variable angle of view of the *in situ* data resulting from rough seas (D. Toole, UCSB, personal communication). Further, linear slopes of beam attenuation (c) versus sediment concentration for the Witte *et al.* (1981) sediment (c550 = $0.86\,{\rm m}^{-1}\,{\rm mg}^{-1}\,{\rm l}$; c750 = $0.60\,{\rm m}^{-1}\,{\rm mg}^{-1}\,{\rm l}$; for both, $R^2 > 0.99$, n = 7) were similar to slopes from the Santa Clara River plume sediment (c660 = $0.84\,{\rm m}^{-1}\,{\rm mg}^{-1}\,{\rm l}$; $R^2 = 0.78$, n = 28, see Warrick (2002) for data collection and processing methods). These data are similar to the maximum c660 slopes reported by Baker and Lavelle (1984) of $0.7 - 0.8\,{\rm m}^{-1}\,{\rm mg}^{-1}\,{\rm l}$, suggesting clay and fine silt particle sizes (2–10 μ m).

A nonlinear calibration was developed for the SMA by computing F_i of the entire set of Witte *et al.* (1981) calibration data. The nonlinear spectral effects of water–sediment mixtures are incorporated in the final suspended sediment concentration estimate through the use of multiple ρ_w measurements in this calibration.

5. Results

Over 220 SeaWiFS cloud-free images were obtained for the period of October 1997 to May 2000 and used in the SMA technique. Using SeaWiFS L1b radiance



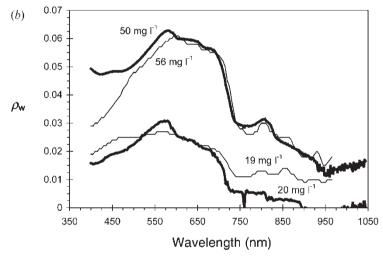


Figure 1. Water-leaving reflectance (ρ_w) spectra utilized in the SMA. (a) Water-sediment mixtures spectra of Witte et al. (1981) utilized for SMA calibration. Reflectance curves are labelled with suspended sediment concentration in mg1⁻¹. Digitized by Mertes (1990). (b) Comparison of in situ Santa Clara River plume water-leaving reflectance spectra (thick lines) from Toole and Siegel (2001) and laboratory reflectance spectra (thin lines) from Witte et al. (1981). Sediment concentration of each spectra is given in mg1⁻¹.

data, total reflectance values (ρ_t) were calculated and are presented for the February 9 1998 image in figure 2(a). For all wavelengths ρ_t is greatest near the Santa Clara River mouth and decreases with distance from the mouth, which qualitatively indicated decreasing suspended sediment concentrations with distance offshore. Also shown is the 'dark pixel' (ρ_{atm}) chosen from the ocean using the criteria described above. The $\rho_t(\lambda)$ of this dark pixel were subtracted from each SeaWiFS band using equation (4), which produced the ocean $\rho_w(\lambda)$ data shown in figure 2(b). Included with the ρ_w data are two laboratory measurements of reflectance from Witte et al. (1981) convolved to the SeaWiFS bands (figure 2(b)). The highest ρ_w in the SeaWiFS and laboratory results differ only by a maximum of 10%. Also shown

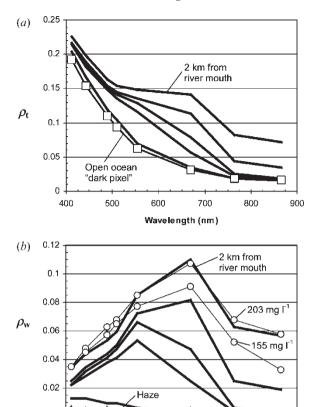


Figure 2. (a) Total reflectance (ρ_t) of the Santa Barbara Channel on February 9, 1998 from SeaWiFS. Bold curves are data sampled at 5 km intervals west of a pixel 2 km from the Santa Clara river mouth. An open ocean 'dark pixel' (see text) is shown with squares. (b) SeaWiFS water reflectance (ρ_w) following the removal of the 'dark pixel' reflectance. An offshore haze pixel is shown with triangles. Laboratory data from Witte et al. (1981) convolved to SeaWiFS bands are shown with circles.

600

700

Wavelength (nm)

800

900

0 |2 400

500

in figure 2(b) are the ρ_w of bright haze over non-turbid water. The spectral response of haze is much lower than that of the river plume.

5.1. *Imagery*

Results for the most extensive river plumes observed in the three years of SeaWiFS data are shown in figure 3. Large plumes are seen in the eastern channel near the mouths of the Santa Clara and Ventura rivers and extend well (10–30 km) into the channel. These three images were all obtained during the 1997–1998 El Niño winter, when extensive flooding was observed throughout California. In contrast, river plumes during the subsequent two winters were not observed greater than 10 km from the coast.

5.2. Error estimation

Many steps are incorporated into the SMA algorithm, each potentially producing errors. SeaWiFS sensor degradation has been quantified and is included in calibration calculations (Eplee and Barnes 2000, Eplee *et al.* 2000), and the

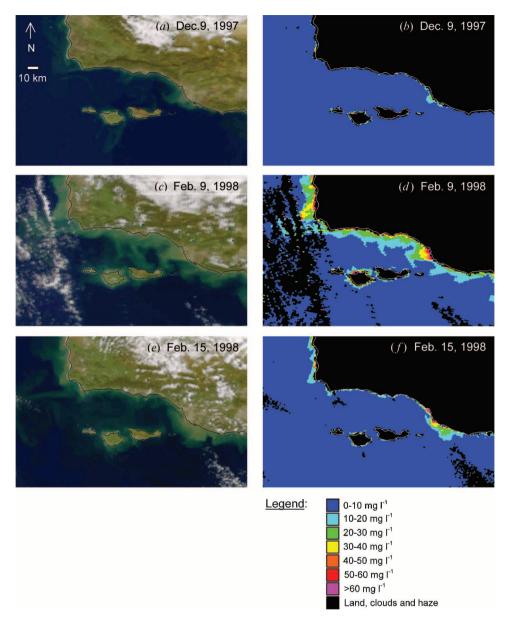


Figure 3. True-colour (a), (c) and (e) and SMA-derived suspended sediment concentrations (b), (d) and (f) of the Santa Barbara Channel region using SeaWiFS. (a) and (b) 11 December 1997; (c) and (d) 11 February 1998; (e) and (f) 15 February 1988.

uncertainty of the radiometric calibration is 0-4% depending on band (Eplee and McClain 2000, Robinson and Wang 2000). These calibration uncertainties will result in maximum uncertainties that scale with SMA sediment concentration output: $5 \,\mathrm{mg}\,\mathrm{l}^{-1}$ error at $50 \,\mathrm{mg}\,\mathrm{l}^{-1}$, increasing to $20 \,\mathrm{mg}\,\mathrm{l}^{-1}$ at $200 \,\mathrm{mg}\,\mathrm{l}^{-1}$. Therefore, a maximum error of 10% across concentrations is predicted.

The dark-pixel atmospheric calibration is another potential source of error, since non-turbid waters are assumed black. Although not perfectly black, measurements of Santa Barbara Channel $\rho_{\rm w}$ for 555–865 nm are typically low. Adding mean values of

Santa Barbara Channel $\rho_{\rm w}$ during 1996–1999 of 0.0027, 0.0006, 0.0003 and 0.0002 for bands 555, 670, 765 and 865, respectively (Toole and Siegel 2001), increased the estimated suspended sediment concentration by a maximum of 5 mg l⁻¹.

Error may also be associated with haze, cdom and chlorophyll. Although rare, haze pixels were observed as unfiltered in some images and produced 5–10 mg l⁻¹ error in the sediment concentration output. Further, it is not unreasonable that cdom and chlorophyll pigments may produce an error of up to 10 mg l⁻¹ (Stumpf and Pennock 1989).

Finally, the SMA calculations and calibration can be the source of error in the final output. Although the optical qualities of the calibration data are very similar to field measures of the plume, some spectral differences between the two data sources are likely. However, the rms errors (ε) were lower than the rms of the Witte *et al.* (1981) laboratory data, which indicated consistent spectral relationships. A maximum error of $10 \, \mathrm{mg} \, \mathrm{l}^{-1}$ can be expected from the SMA, considering these rms errors.

In summary, if the radiometric and atmospheric calibrations were perfect and if there were no cdom or chlorophyll, the estimated error for the SMA sediment concentration estimates is ca $10\,\mathrm{mg}\,\mathrm{l}^{-1}$. Assuming minor errors associated with each of the calibrations, an error of approximately $\pm 20\,\mathrm{mg}\,\mathrm{l}^{-1}$ for the suspended sediment concentration algorithm is predicted.

6. Conclusions

A spectral mixture analysis algorithm was developed to estimate suspended sediment concentrations in SeaWiFS imagery for the Santa Barbara Channel, California. The Santa Barbara Channel algorithm was calibrated with laboratory measurements of reflectance, which produced suspended sediment estimates between $0\,\mathrm{mg}\,\mathrm{l}^{-1}$ and $200\,\mathrm{mg}\,\mathrm{l}^{-1}$. Errors were predicted to be $\pm\,20\,\mathrm{mg}\,\mathrm{l}^{-1}$. Suspended sediment in the channel was observed primarily over the eastern channel where the major river systems discharge.

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